

RADIOWAVE SCATTERING AND ULTRA-LONG-BASELINE INTERFEROMETRY

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Abstract

Interstellar scattering can irretrievably blur the images of compact radio sources when examined with extremely high resolution. Because of this effect, diffraction-limited observations of extragalactic sources with an Earth-Moon baseline will only be possible at frequencies above about 7 GHz, in which case the resolution will be $\lesssim 20$ μ arcsec. Preliminary observations to determine the potential usefulness of such resolving power are discussed. The simplest of these would consist of a search for interstellar scintillations in compact sources at 10 GHz, which would provide an effective resolution about equal to that of an Earth-Moon baseline at this frequency. Also important in this context is the development of very-long-baseline interferometry (VLBI) in near-Earth orbit, as any ultra-high-resolution observations (such as with an Earth-Moon baseline), if appropriate, would require intermediate baselines for mapping.

Introduction

I wish to address two questions concerning ultra-long-baseline interferometry. First, what are the fundamental limitations imposed by scattering due to irregularities in the interplanetary medium (IPM) and the interstellar medium (ISM)? Second, what, if anything, can be learned in advance about possible source structure on the 10^{-5} -arcsec scales that would be probed using an Earth-Moon interferometer?

Interplanetary and Interstellar Scattering

A fundamental difference between interplanetary scattering (IPS) and interstellar scattering (ISS) should be noted at the outset. At most frequencies ν and solar elongations ϵ likely to be used (e.g., $\nu > 1$ GHz and $\epsilon \gtrsim 5^\circ$), IPS is weak. This means that each antenna in the interferometer will undergo an independent time-varying phase shift due to a changing refractive index along each path in the IPM. If the integration time is less than the scintillation time scale, then the fringes are not destroyed (although they would fluctuate in amplitude and phase because of scintillation), and image restoration is possible, in principle. Conversely, ISS is strong for many situations of interest ($\nu \lesssim 10$ GHz at high galactic latitudes and up to considerably higher frequencies at low galactic latitudes). Physically, this roughly corresponds to a different propagation phase shift, not only for each antenna, but also for each part of the source covered by an independent phase blob of size L . The radiation is scattered over an angular distribution $\theta_s \approx \lambda/L$. (See fig. 1.) An extragalactic source seen at high galactic latitude, the intrinsic size θ_I of which is in the range

$$L/z \approx (2 \mu\text{arcsec}) \nu_1^{1.2} \lesssim \theta_I \lesssim \theta_s \approx (1 \text{ marcsec}) \nu_1^{-2.2}$$

will have an apparent size $\approx \theta_s$, and its intrinsic structure will be irretrievably lost, even if the integration time and bandwidth are smaller than the time and frequency scales characterizing the scintillation (ref. 1). (In the preceding expression, z is the distance to the scattering "screen," taken to be 250 pc, and ν_1 is in gigahertz.) Of course, the structure of a component smaller in angular size than a phase blob may possibly be recoverable, providing an interferometer having sufficient resolution is used. An Earth-Moon interferometer is capable of resolving structure on scales $< L/z$, at frequencies above 10 GHz (at which level ISS becomes weak at high galactic latitudes, anyway).

Interplanetary Scattering

The degree of decorrelation is determined by the solar elongation and frequency of any particular observation. The locus of parameters for which the decorrelation on an Earth-Moon baseline exceeds 10% is shown in figure 2. The integration time is assumed to be longer than the scintillation time scale, and the scattering is assumed to be weak (which is not strictly true for very small elongation). This assumption is based upon the power spectrum of phase fluctuations measured when the Sun was not in a highly active state (ref. 2). During sunspot maximum, the area of 10% decorrelation and greater may need to be extended by a factor of about 2 (in frequency) above the 90% correlation line shown.

Clearly, IPS does not necessarily present serious problems for such ultra-high-resolution observations at gigahertz frequencies, particularly if small to moderate elongations are avoided. Residual effects caused by this "atmosphere" of the solar system could probably be removed using existing self-calibration techniques.

Interstellar Scattering

The scattering material in the galaxy is distributed in a complex manner, with at least two components (and probably more): (1) a large filling-factor medium with quite large scale height, perhaps 0.5 kpc; and (2) a very low filling-factor medium, consisting perhaps of distinct clumps, and distributed with low scale height (i.e., $\lesssim 100$ pc) (ref. 3). The high-galactic-latitude lines of sight interesting to extragalactic astronomers are typically affected by medium 1 only, and the range of intrinsic sizes blurred by ISS, given previously, was estimated accordingly. Evidently, paths traversing more than one to a few kiloparsecs in the galactic plane intercept one or more type 2 clumps, which result in heavy scattering.

Of particular interest in the context of an Earth-Moon interferometer is the frequency ν^* , above which the scattering size θ_s is smaller than the resolving angle $\theta_R \approx \lambda/B$, where B is the Earth-Moon baseline. This frequency is given in table I for several directions of possible interest. That the full power of the Earth-Moon baseline would be available for extragalactic research at frequencies typically above 7 GHz is shown in table I. It should be noted that because of the inhomogeneity of the scattering medium, even along high-galactic-latitude paths, this estimate will probably vary by about a factor of 2 from one line of sight to the next. Long paths in the plane are so severely affected by scattering that such an interferometer is probably not useful over the radio range for examining distant compact sources near the galactic plane. It is also known that the apparent scattering size fluctuates greatly from one line of sight to the next and, in some cases, is considerably greater than the 50 mas given. On the other hand, nearby galactic sources (closer than ≈ 1 kpc) are likely affected to a degree comparable with or even less than extragalactic sources. Hence, such sources could possibly be probed with the full resolution, at sufficiently high frequencies. Of some interest may be burst regions on nearby stars, as discussed by Burns (ref. 4).

Existence of 10^{-5} -Arcsecond Sources

As we have seen, in most situations, ISS limits the usable frequencies to $\gtrsim 7$ GHz, if the full resolving power of the Earth-Moon baseline is to be realized. At these frequencies, $\theta_R < 20$ μ arcsec. This immediately raises the question: Are there sources (or components) small enough to show a significant (yet not unresolved) fringe visibility on this baseline? Fortunately, we can probably answer this question before baselines are extended to the Moon. In particular, there are three observational approaches that should be preliminary to the development of an Earth-Moon baseline.

These observational approaches will be described after a brief discussion of this question in the context of known categories of radio sources that may not be hopelessly blurred by the heavy scattering in the galactic disk. Pulsars, if not broadened by scattering, would almost certainly be unresolved even on the Earth-Moon baseline (ref. 5). Active regions on some stars may very well subtend angular sizes ≈ 5 μ arcsec at kiloparsec distances and might be profitably studied with the resolution that an Earth-Moon interferometer can provide (ref. 4). In this case, the primary limitation is sensitivity. Of the various types of molecular masers, nearby H_2O masers offer the best prospects for extreme apparent compactness (of the individual spots). Also, H_2O masers in distant galaxies would appear quite small, although, of course, sensitivity is likely to be a problem. Finally, extragalactic continuum sources are thought to be limited to brightness temperatures $< 10^{12}$ K, as a consequence of the incoherent electron-synchrotron emission mechanism. If this limitation applies, as appears to be the case, then 20- μ arcsec extragalactic continuum sources would necessarily be fairly weak ($\lesssim 10$ mJy) (ref. 4). The first of three suggested preliminary observational strategies concerns the possibility that weak compact extragalactic sources might require an Earth-Moon baseline to be resolved. In what follows, these observations are discussed.

1. Earth-based VLBI observations of weak (< 100 mJy) compact extragalactic sources — The question to be addressed here is: Why are weak compact sources weak? Is it because they are small in angular size, yet have very high brightness temperatures, close to the Compton limit ($\approx 10^{12}$ K), or because they have lower brightness temperatures and angular sizes perhaps comparable to the well-studied stronger sources? Of course, the answer could lie somewhere between these two explanations. A systematic, high-sensitivity survey of a carefully selected sample, using available Earth-based baselines, could probably shed some light on this question. Of course, it could never tell us whether sources are as small as 20 μ arcsec. Nevertheless, a finding that weak sources tend to be smaller or unresolved would be a very interesting result.

2. Development of space VLBI — Several projects have been proposed (e.g., Quasat and the Russian space VLBI project) that would extend baselines into space in the near future. On the longer term, Weiler and his colleagues (ref. 6) have outlined a space-based array with baselines as long as the Astro-Array, or roughly 10^5 km. This is a logical goal for radio interferometry, given our current understanding of compact radio sources. Such an array would provide a good indication as to whether longer baselines, as would be provided by a lunar-based element, are needed. A lunar-based element could then operate as an "outrigger" to the Astro-Array, which would, of course, provide the intermediate baselines required for mapping.

3. Observational search for interstellar scintillation at 10 GHz — Such observations could achieve a resolution equivalent to that of an Earth-Moon baseline, but at negligible "cost." Fast interstellar scintillation is caused by interference in the scattered radiation reaching the observer along various ray paths. The effective resolution afforded by this technique is just the angle subtended by the phase blobs in the ISM; i.e., L/z . Sources smaller than L/z in angular size exhibit fully developed random interference fringes (i.e., scintillations) as observed in pulsars. Sources larger than L/z are resolved and therefore have smaller scintillation "visibility," of approximate magnitude $(L/z)/\theta_1$. Observations of interstellar scintillation would probably not be particularly

useful for mapping intrinsic structure. Nevertheless, these observations would provide a very effective means of detecting ultracompact components.

Thus far, searches for diffractive interstellar scintillation in extragalactic sources have been negative (refs. 7 to 10). Most of these observations, however, were conducted at low frequencies (< 0.5 GHz) where L is quite short ($L = v_1 \times 10^{4.8}$ km); therefore, any fully scintillating components would have to be extremely compact ($\theta_l < 2$ μ arcsec). At higher frequencies, the effective resolving angle increases with L until v_* is reached, above which the scintillations are weak with scale $L_* \approx \sqrt{\lambda z}$. For typical high-galactic-latitude paths, $v_* \approx 10$ GHz. For such lines of sight (to extragalactic sources), the effective resolution just becomes equivalent to that of an Earth-Moon baseline at about 10 GHz! That is, at 10 GHz, $L \approx L_* \approx 6 \times 10^5$ km, and $L/z \approx 15$ μ arcsec $\approx \lambda/B$, where $B \approx 4 \times 10^5$ km is the Earth-Moon baseline. Therefore, an extragalactic source compact enough to produce a significant fringe visibility on an Earth-Moon baseline should also exhibit a comparable scintillation "visibility." This premise is indicated schematically in figure 3, which shows the approximate frequency dependence of the interferometric and scintillation visibilities of a 20- μ arcsec component.

Clearly, interstellar scintillations should be searched for in compact extragalactic sources at about 10 GHz. At this frequency, the correlation bandwidth of any scintillations will be large, and thus the search will have to be conducted in the time domain (rather than the frequency domain). The expected time scale is approximately $L/(50 \text{ km sec}^{-1}) \approx 3$ hr. It should be noted that Condon and Backer (ref. 7) failed to detect any scintillations in 12 sources at 8.1 and 2.7 GHz. More extensive observations should be conducted, however.

It is widely suspected that the "flicker" reported by Heeschen (refs. 11 and 12) and Simonetti et al. (ref. 13) may be a form of scintillation, quite possibly refractive in origin. This suspicion should be confirmed, however, and its possible utility as a signature of compact structure should be examined.

It may also be possible to apply this technique to fairly nearby radio sources in the galaxy (closer than about 1 kpc). More distant galactic sources would have significant probability of being seen through regions of heavy scattering in the disk, which, if intercepted, would cause the effective resolving angle to be very small. In such a case, the absence of scintillations would not be informative concerning the expected visibility on an Earth-Moon baseline.

Conclusions

If the full resolving power of an Earth-Moon baseline is to be realized, then it must be used at frequencies above 7 GHz (plus or minus a factor of 2), to avoid unrecoverable image degradation due to interstellar scattering. For lines of sight passing through more than about a kiloparsec of the galactic disk, this constraint is much more severe, such that many distant galactic sources would not be observable on this baseline at radiofrequencies.

At 7 GHz, the diffraction-limited resolution of an Earth-Moon interferometer is about 20 μ arcsec. Before deploying an interferometer element on the Moon, we should attempt to determine whether any known radio sources have structure on this scale. Fortunately, it is possible to sample "astronomical phase space" at such resolutions ($\approx 10^{-5}$ arcsec) and frequencies (≈ 10 GHz) by searching for interstellar scintillation of compact sources. Such investigations could guide the development of ultra-long-baseline interferometry much as interplanetary scintillation observations provided direct evidence for compact (< 1 arcsec) structures in quasars and active galactic nuclei and thus further motivated the development of VLBI.

Should an Earth-Moon baseline be required, then considerable filling-in with intermediate baselines will also be required for mapping. Clearly, the long-term development of radio interferometry in Earth orbit is a reasonable goal (ref. 6), both in terms of usefulness for presently envisioned investigations and in terms of providing a complement to a possible lunar-based element.

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TABLE I.- TYPICAL SCATTERING PARAMETERS

Line of sight	θ_s (1 GHz), arcsec	ν^* , Hz
$a b > 20^\circ$; extragalactic	1×10^{-3}	7×10^9
$ b < 2^\circ$; distance > 5 kpc	50×10^{-3}	300×10^9
To galactic center	1	$1 \times 10^{13.8}$

$^a b$ = galactic latitude.

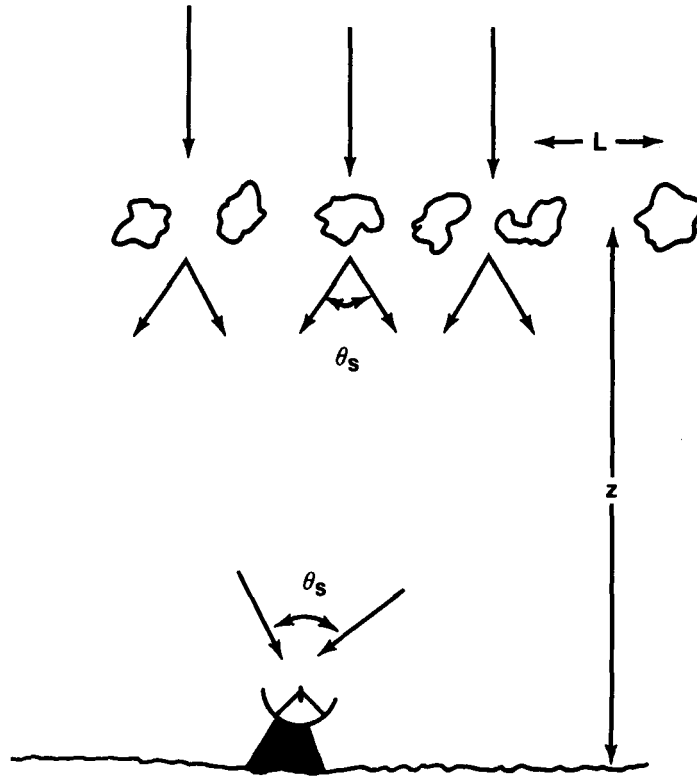


Figure 1.- Geometry of interstellar scattering.

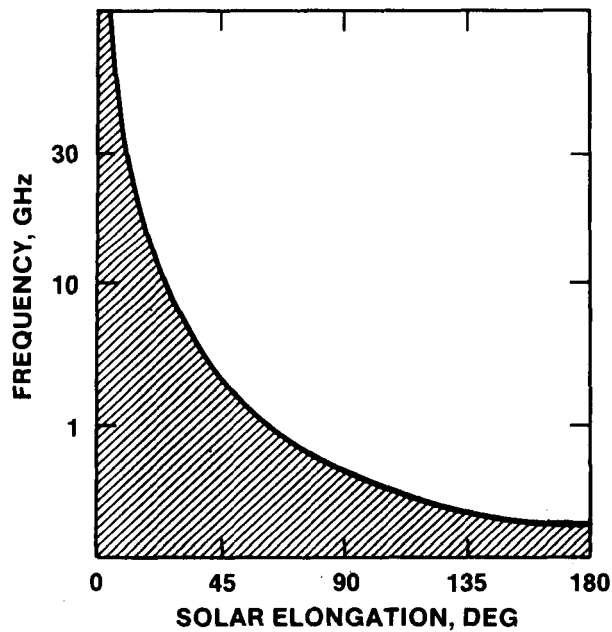


Figure 2.- Parameter space for interplanetary scattering, under typical solar-minimum conditions. If the integration time exceeds the time scale for interplanetary scintillation, observations in the shaded domain will undergo decorrelation of greater than 10%. The assumed baseline is 4×10^5 km.

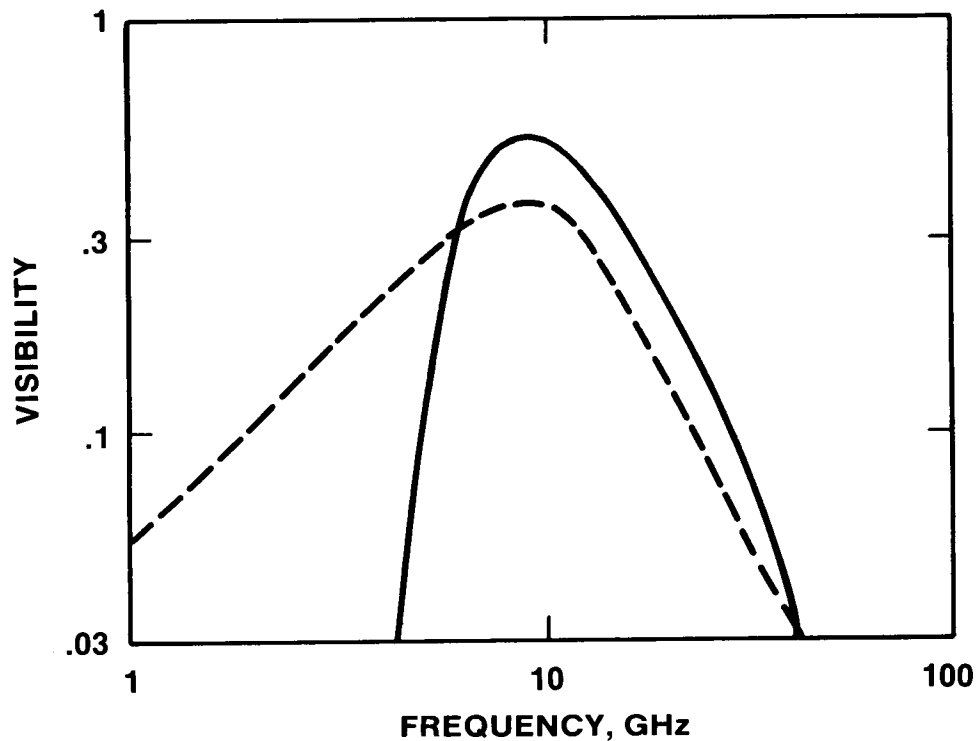


Figure 3.- Schematic illustration of the interferometric (solid line) and scintillation (dashed line) visibilities of a homogeneous 20- μ arcsec component. Below a frequency of approximately 7 GHz, the interferometric visibility is reduced because of ISS; above 7 GHz, interferometric visibility is reduced because of overresolution on the assumed baseline of 4×10^5 km. The scintillation visibility is reduced at a frequency below approximately 10 GHz because of "overresolution" of the source by the decreasing blob size. (L is roughly proportional to v .) Above 10 GHz, the scintillation is weak and thus the scintillation strength decreases.